Physics for Science Phys 101

Chapter 4 (Part 1)

Fluid Mechanics (Fluid static)

Prof. Dr. Moustafa Tawfik Ali Ahmed

Objectives: After completing this Chapter, you should be able to:

- Define and apply the concepts of **density** and **fluid pressure** to solve physical problems.
- Define and apply concepts of **absolute**, معيار اومقياس **gauge**, and **atmospheric** pressures.
- State **Pascal's law** and apply for input and output pressures.
- State and apply **Archimedes' Principle** to solve physical problems.

Introduction

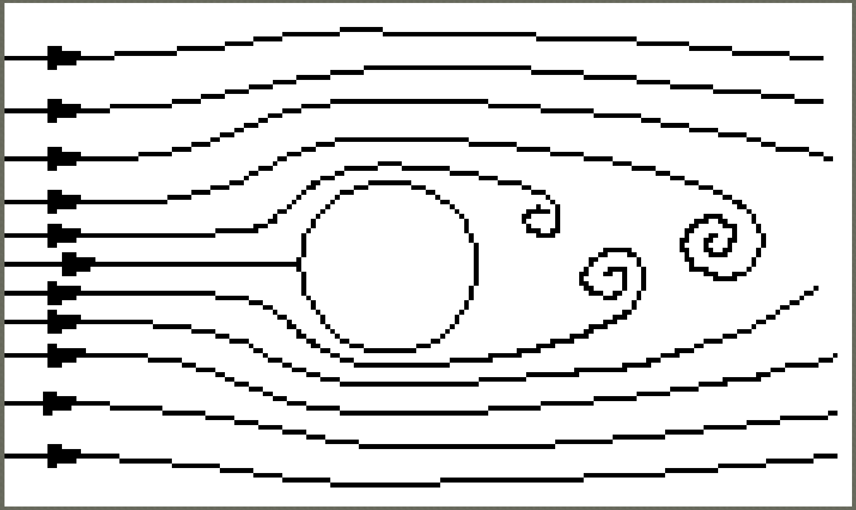
Field of Fluid Mechanics can be divided into 3 branches:

- **Fluid Statics: mechanics of fluids at rest**

- **Fluid Dynamics: deals with the relations between velocities and accelerations and forces exerted by or upon fluids in motion**

Streamlines

A streamline is a line that is tangential to the instantaneous velocity direction (velocity is a vector that has a direction and a magnitude)

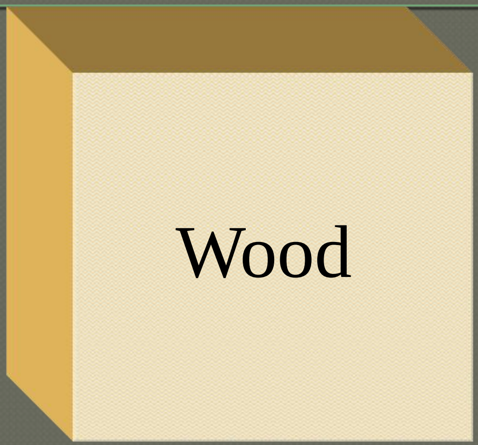


Instantaneous streamlines in flow around a cylinder

Mechanics of fluids is extremely important in many areas of engineering and science. Examples are:

- Biomechanics
  - Blood flow through arteries تدفق الدم فى الشرايين ا
  - Flow of cerebral fluid تدفق السائل الدماغي
- Meteorology and Ocean Engineering
  - Movements of air currents and water currents
- Chemical Engineering
  - Design of chemical processing equipment

Mass Density



2 kg, 4000 cm^3

$$Density = \frac{mass}{volume}; \quad \rho = \frac{m}{V}$$

Lead: 11,300 kg/m^3

Wood: 500 kg/m^3

4000 cm^3

45.2 kg

Same volume

177 cm^3

2 kg

Same mass

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Example 1: The density of steel is 7800 kg/m^3. What is the volume of a 4-kg block of steel?

$$\rho = \frac{m}{V}; \qquad V = \frac{m}{\rho} = \frac{4\ \text{kg}}{7800\ \text{kg/m}^3}$$

$$\boxed{V = 5.13 \times 10^{-4}\ \text{m}^3}$$

What is the mass if the volume is 0.046 m^3?

$$m = \rho V = (7800\ \text{kg/m}^3)(0.046\ \text{m}^3);$$

$$\boxed{m = 359\ \text{kg}}$$

Relative Density

The relative density ρ_r of a material is the ratio of its density to the density of water ($1000\ kg/m^3$).

$$\boxed{\rho_r = \frac{\rho_x}{1000\ \text{kg/m}^3}}$$

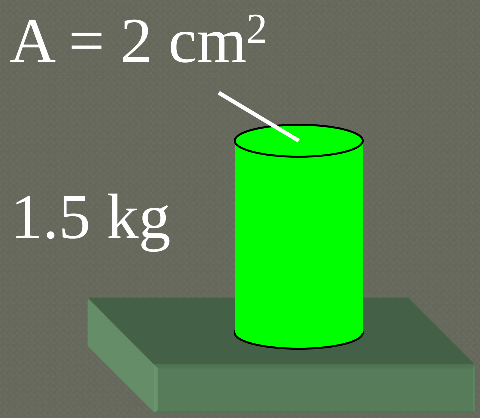
Examples:

Steel ($7800\ kg/m^3$)	$\rho_r = 7.80$
Brass ($8700\ kg/m^3$)	$\rho_r = 8.70$
Wood ($500\ kg/m^3$)	$\rho_r = 0.500$

Pressure

Pressure is the ratio of a force F to the area A over which it is applied:

$$\text{Pressure} = \frac{Force}{Area}; \qquad P = \frac{F}{A}$$



$$P = \frac{F}{A} = \frac{(1.5\text{ kg})(9.8\text{ m/s}^2)}{2 \text{ x } 10^{-4}\text{ m}^2}$$

$$P = 73{,}500\ \text{N/m}^2$$

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The Unit of Pressure (Pascal):

A pressure of one pascal (1 Pa) is defined as a force of one newton (1 N) applied to an area of one square meter (1 m^2).

$$\text{Pascal:} \quad 1\ \text{Pa} = 1\ \text{N/m}^2$$

In the previous example the pressure was 73,500 N/m^2. This should be expressed as:

$$\boldsymbol{P} = 73{,}500\ \text{Pa}$$

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Units for Pressure

Unit	Definition or Relationship
1 pascal (Pa)	1 kg m^{-1} s^{-2}
1 bar	1 x 10^5 Pa
1 atmosphere (atm)	101,325 Pa
1 torr	1 / 760 atm
760 mm Hg	1 atm
14.696 pounds per sq. in. (psi)	1 atm

Absolute and Gage Pressure

- **Absolute pressure: The pressure of a fluid is expressed relative to that of vacuum**

- **Gage pressure: Pressure expressed as the difference between the pressure of the fluid and that of the surrounding atmosphere.**

- **Usual pressure gages record gage pressure. To calculate absolute pressure**:

$$P_{abs} = P_{atm} + P_{gage}$$

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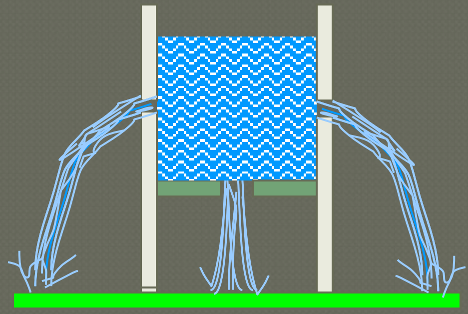
Fluid Pressure

A liquid or gas cannot يعانى من sustain a shearing stress - it is only restrained by a boundary. Thus, it will exert a force against and perpendicular to that boundary.

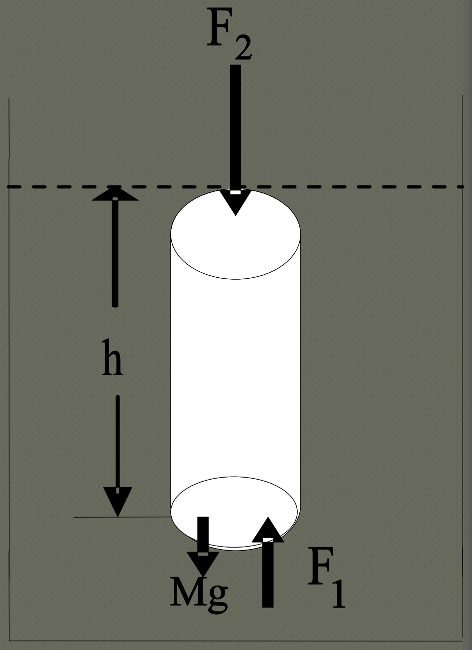
- The force F exerted by a fluid on the walls of its container always acts perpendicular to the walls.



Water flow shows ⊥ F

Variation of Pressure with depth in Fluid

Assume we have an imaginary cylinder of incompressible liquid at rest of density ρ *and cross- sectional area* A *and depth* h *from surface*



The pressure of liquid on the bottom face is P *and on top face is* P_o

The upward force on bottom face is $F_1 = P A$
The downward force on the top face is $F_2 = -P_o A$
The weight of the cylinder is $Mg = -\rho A h g$
The cylinder is in equilibrium, net force = zero

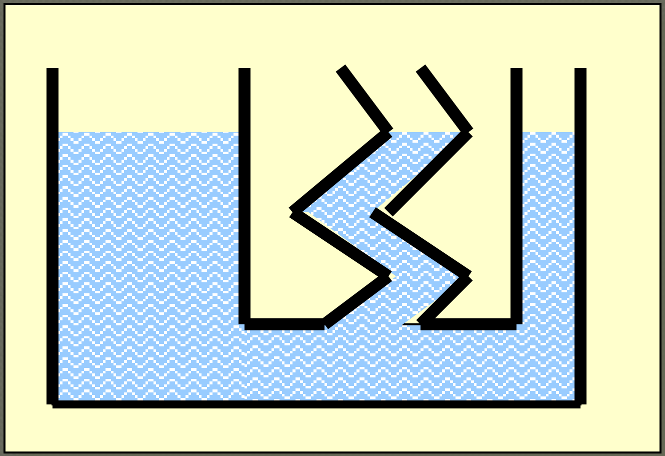
$P A - P_o A - Mg = 0$ *or* $P A - P_o A - P A h g = 0$
$\Rightarrow P = P_o + \rho g h$

P_o *is atmospheric pressure,* $P_o = 1$ atm $= 1.013 \times 10^5$ Pa

$$P = \rho g h$$

Independence of Shape and Area.

Water seeks its own level, indicating that fluid pressure is independent of area and shape of its container.



- At any depth h below the surface of the water in any column, the pressure P is the same. The shape and area are not factors.

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Properties of Fluid Pressure

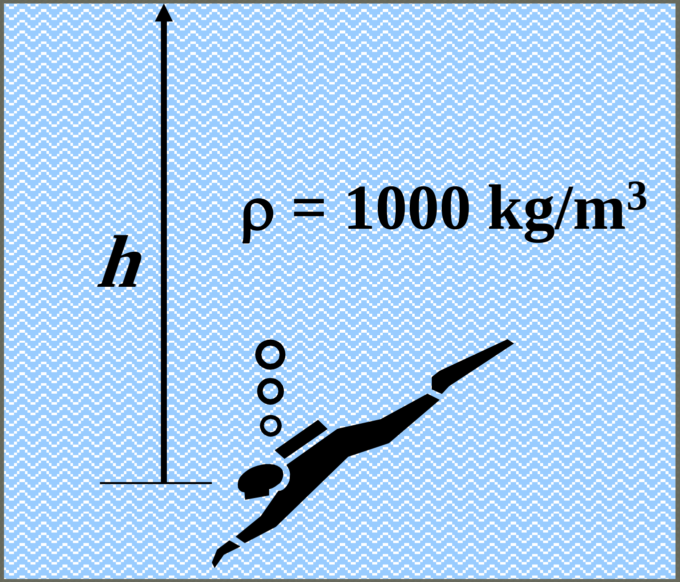
- The forces exerted by a fluid on the walls of its container are always perpendicular.
- The fluid pressure is directly proportional to the depth of the fluid and to its density.
- At any particular depth, the fluid pressure is the same in all directions.
- Fluid pressure is independent of the shape or area of its container.

Example 2. A diver is located 20 m below the surface of a lake (ρ = 1000 kg/m^3). What is the pressure due to the water?

The difference in pressure from the top of the lake to the diver is:

$$\Delta P = \rho g h$$

h = 20 m; g = 9.8 m/s^2



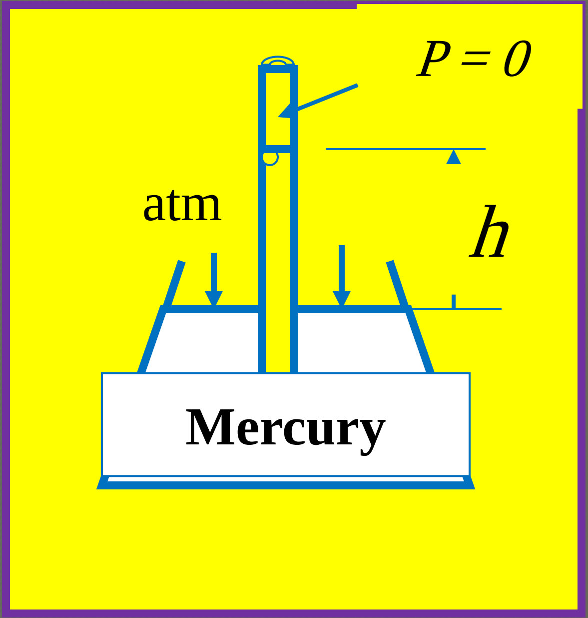
$$\Delta P = (1000\text{ kg/m}^3)(9.8\text{ m/s}^2)(20\text{ m})$$

$$\boxed{\Delta P = 196\text{ kPa}}$$

Atmospheric Pressure

atm

One way to measure atmospheric pressure is to fill a test tube with mercury, then invert it into a bowl وعاء of mercury.



Density of Hg = 13,600 kg/m^3

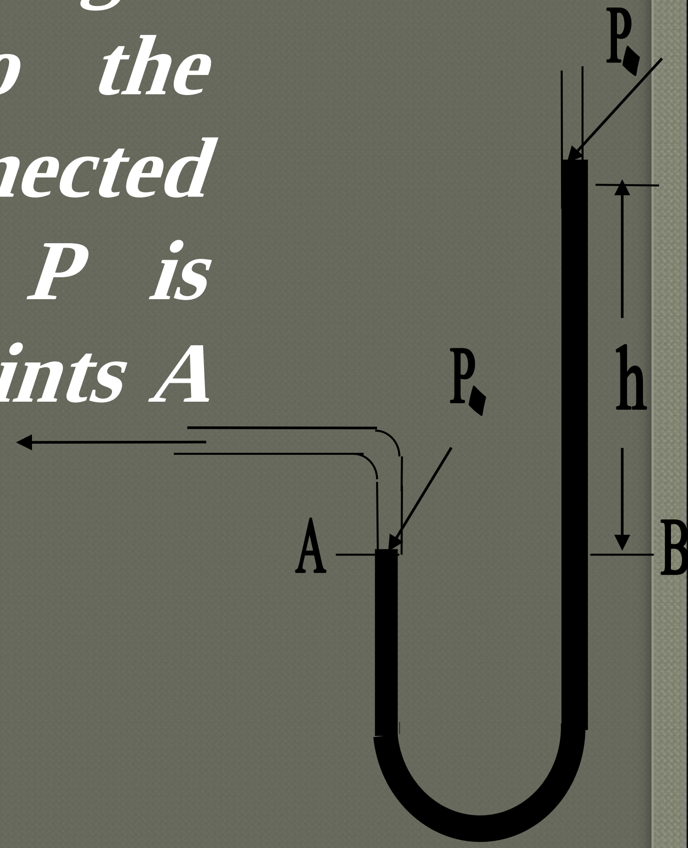
$$P_{atm} = \rho g h \qquad h = 0.760 \text{ m}$$

$$P_{atm} = (13{,}600 \text{ kg/m}^3)(9.8 \text{ m/s}^2)(0.760 \text{ m})$$

$$\boxed{P_{atm} = 101{,}300 \text{ Pa}}$$

The Open –Tube Manometer

It is U- shaped tube containing a liquid; one end is open to the atmosphere and the other connected to a tank whose pressure P is unknown. The pressures at points A and B must be the same.



$$P = P_o + \rho gh$$

or

$$P - P_o = \rho gh$$

The pressure P is called the absolute pressure.

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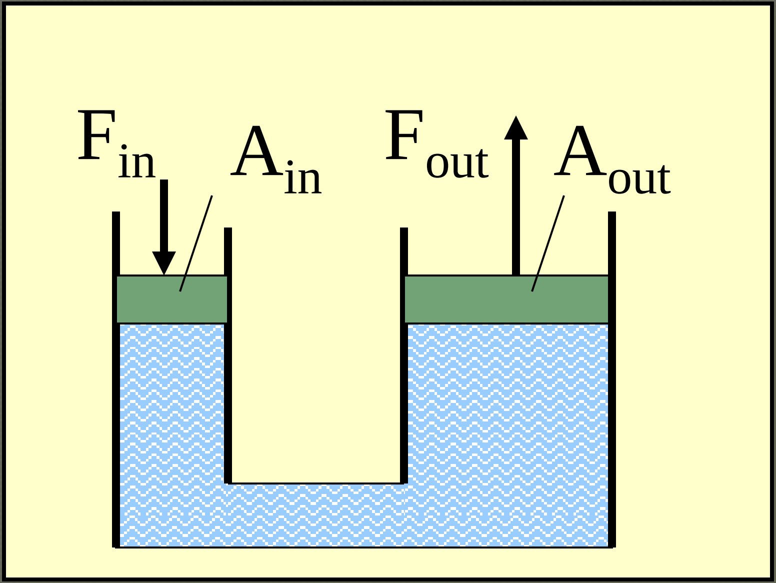
Pascal's Law

<u>Pascal's Law:</u> An external pressure applied to an enclosed fluid is transmitted uniformly throughout the volume of the liquid.



Pressure in = Pressure out

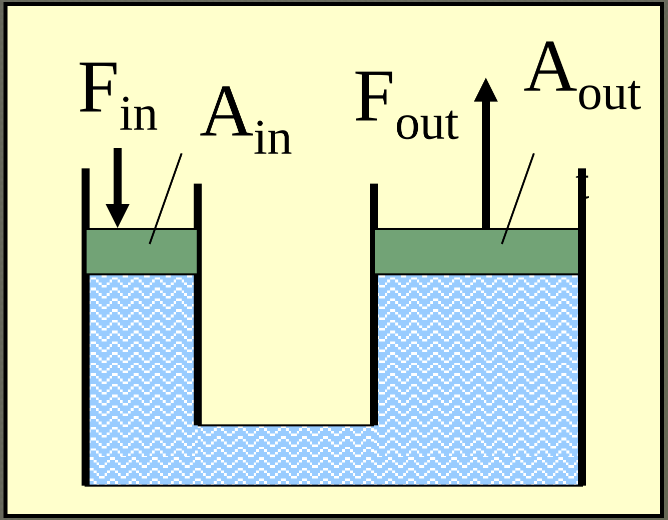
$$\frac{F_{in}}{A_{in}} = \frac{F_{out}}{A_{out}}$$

Example 3. The smaller and larger pistons of a hydraulic press have diameters of 4 cm and 12 cm. What input force is required to lift a 4000 N weight with the output piston?

$$\frac{F_{in}}{A_{in}} = \frac{F_{out}}{A_{out}}; \quad F_{in} = \frac{F_{out}A_{in}}{A_{out}}$$

$$R = \frac{D}{2}; \quad Area = \pi R^2$$

$$F_{in} = \frac{(4000\text{ N})(\pi)(2\text{ cm})^2}{\pi(6\text{ cm})^2}$$



R_{in} = 2 cm; R = 6 cm

$$F = 444\text{ N}$$

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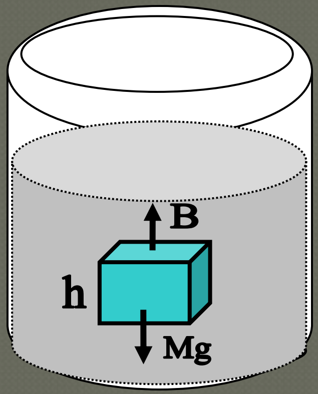
Archimedes' Principle

The magnitude of the buoyant force always equals the weight of the fluid displaced by the object.

Verification of Archimedes principle

If a cube of height h *immersed in a liquid of density* ρ_{fluid}*, the pressure at top and bottom faces are* P_1 *and* P_2 *respectively,*

Where $P_2 = P_1 + \rho\, g\, h$



The pressure at the bottom of the cube causes an upward forceequals P_2A.
The pressure at the top of the cube causes a downward force equals $-P_1\, A$.
Where A *is the area of face of the cube,*
The resultant force is the buoyant force *B*, *Where*

$$B = (P_2 - P_1)\, A = \rho_{fluid}\, g\, h\, A = \rho_{fluid}\, g\, V$$

V *is the volume of the fluid displaced by the cube. Because the product* ρV *equals the mass of liquid displaced by the cube,*

so $B = \quad Mg = \rho_{fluid}\, g\, V$

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Special cases

Case 1: Totally Submerged Object

When an object is totally submerged in a fluid of density ρ_{fluid}, the magnitude of the upward buoyant force

$$\mathbf{B} = \mathbf{Mg} = \rho_{\mathrm{fluid}}\, g\, V_{\mathrm{object}}$$

Where V_{object} is the volume of the object. If the object has a mass **M** and density ρ_{object}, its weight (gravitational force) is equal to:

$$F_g = \mathbf{Mg} = \rho_{\mathrm{object}}\, g\, V_{\mathrm{object}}$$

and the net force on it is

$$F_g - B = (\rho_{\mathrm{object}} - \rho_{\mathrm{fluid}})\, g\, V_{\mathrm{object}}$$

1- Hence, if the density of the object is less than the density of the fluid, then the downward gravitational force is less than the buoyant force, and the object float. $F_{net} = (\rho_{obj} - \rho_{fluid})\, V_{obj}$

وبالتالي ، إذا كانت كثافة الجسم أقل من كثافة السائل، ثم قوة الجاذبية (الهبوط) أقل من قوة الطفو، و = بهذا يطفوا الجسم

Special cases

2- If the density of the object is greater than the density of the fluid, then the upward buoyant force is less than the downward gravitational force, and the object sinks $F_{net} = (\rho_{fluid} - \rho_{obj})\, V_{obj}$

إذا كانت كثافة الجسم أكبر من كثافة السائل، ثم قوة الدفع أقل من قوة الجاذبية ، فان الجسم ينغمر

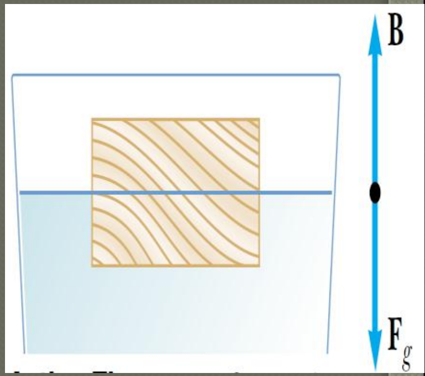
- *3- If the density of the submerged object equals the density of the fluid, the net force on the object is zero and it remains in equilibrium. Thus, the direction of motion of an object submerged in a fluid is determined only by the densities of the object and the fluid.*
- إذا كانت كثافة الجسم المغمور يساوي كثافة السوائل، وقوة كلية على الجسم تساوى صفر ويبقى في حالة توازن. وهكذا، يتم تحديد اتجاه الحركة للجسم المغمورة في السائل فقط بواسطة كثافة الجسم والسوائل

Special cases,

Case 2: Floating Object جسم يطفو

Now consider an object of volume V_{object} and density $r_{object} < r_{liquid}$ floating on the surface of a fluid—that is, an object that is only *partially* submerged

In this case, the upward buoyant force is balanced by the downward gravitational force acting on the object. If V_{fluid} is the volume of the fluid displaced by the object (this volume is the same as the volume of that part of the object that is beneath the surface of the fluid), the buoyant force has a magnitude



$$\mathbf{B} = \rho_{\text{fluid}}\, g\, V_{\text{fluid}}$$

Because the weight of the object is

$$F_g = \rho_{object}\, g\, V_{object}$$

and because $F_g = B$, we see that

$$\rho_{object}\, g\, V_{object} = \rho_{\text{fluid}}\, g\, V_{\text{fluid}}$$

$$\frac{\rho_{\text{fluid}}}{\rho_{\text{object}}} = \frac{V_{\text{object}}}{V_{\text{fluid}}}$$

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Example 4: A 2-kg brass block is attached to a string and submerged underwater. Find the buoyant force and the tension in the rope.

All forces are balanced:

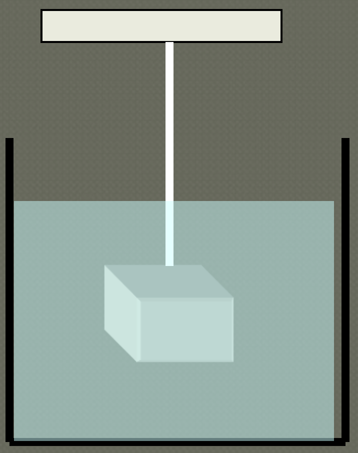
$$F_B + T = mg \qquad F_B = \rho_w g V_w$$

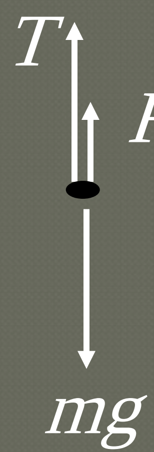
$$\rho_b = \frac{m_b}{V_b}; \quad V_b = \frac{m_b}{\rho_b} = \frac{2\text{ kg}}{8700\text{ kg/m}^3}$$

$$V_b = V_w = 2.30 \times 10^{-4}\text{ m}^3$$

$$F_B = (1000\text{ kg/m}^3)(9.8\text{ m/s}^2)(2.3 \times 10^{-4}\text{ m}^3)$$

$$\boxed{F_B = 2.25\text{ N}}$$





$$F_B = \rho g V$$

Force diagram

Example 4 (Cont.): A 2-kg brass block is attached to a string and submerged underwater. Now find the the tension in the rope.

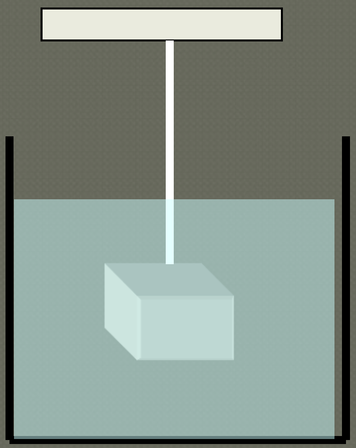
$$\boxed{F_B = 2.25\text{ N}}$$

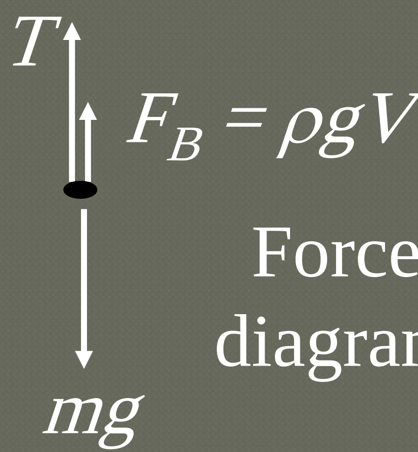
$$F_B + T = mg \qquad T = mg - F_B$$

$$T = (2\text{ kg})(9.8\text{ m/s}^2) - 2.25\text{ N}$$

$$T = 19.6\text{ N} - 2.25\text{ N}$$

$$\boxed{T = 17.3\text{ N}}$$





Force diagram

This force is sometimes referred to as the apparent weight.

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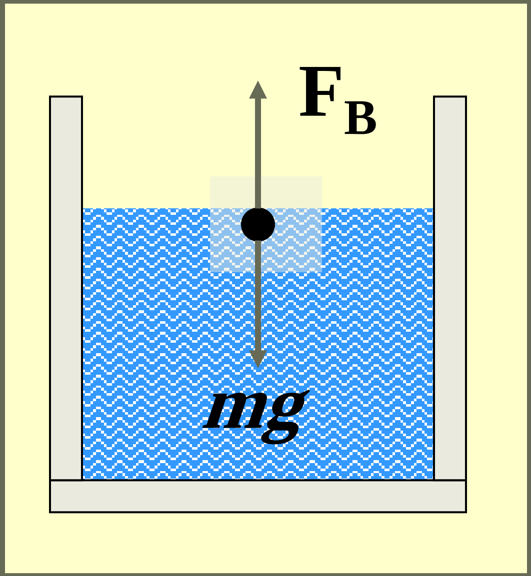
Floating objects:

When an object floats, partially submerged, the buoyant force exactly balances the weight of the object.



$$F_B = \rho_f g V_f$$

$$m_x g = \rho_x V_x g$$

$$\rho_f \cancel{g} V_f = \rho_x V_x \cancel{g}$$

Floating Objects: $\boxed{\rho_f V_f = \rho_x V_x}$

If V_f is volume of displaced water V_{wd}, the relative density of an object x is given by:

Relative Density:

$$\rho_r = \frac{\rho_x}{\rho_w} = \frac{V_{wd}}{V_x}$$

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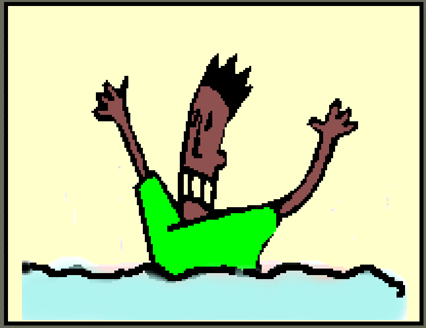
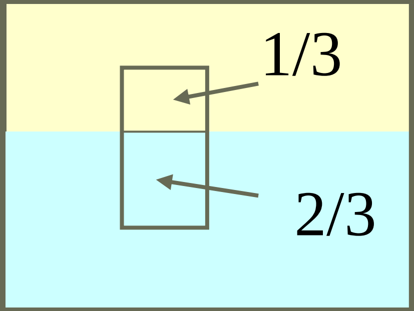
Example 5: A student floats in a salt lake with one-third of his body above the surface. If the density of his body is 970 kg/m^3, what is the density of the lake water?



Assume the student's volume is 3 m^3.

$$V_s = 3\text{ m}^3;\quad V_{wd} = 2\text{ m}^3;\quad \rho_s = 970\text{ kg/m}^3$$

$$\boxed{\rho_w V_{wd} = \rho_s V_s}$$



$$\frac{\rho_s}{\rho_w} = \frac{V_{wd}}{V_s} = \frac{2\text{ m}^3}{3\text{ m}^3};\quad \rho_w = \frac{3\rho_s}{2}$$

$$\rho_w = \frac{3\rho_s}{2} = \frac{3(970\text{ kg/m}^3)}{2}$$

$$\boxed{\rho_w = 1460\text{ kg/m}^3}$$

Problem Solving Strategy

1. Draw a figure. Identify givens and what is to be found. Use consistent units for P, V, A, and ρ.
2. Use absolute pressure P_{abs} unless problem involves a difference of pressure ΔP.
3. The difference in pressure ΔP is determined by the density and depth of the fluid:

$$P_2 - P_1 = \rho g h; \quad \rho = \frac{\mathrm{m}}{\mathrm{V}}; \quad \mathrm{P} = \frac{\mathrm{F}}{\mathrm{A}}$$

Problem Strategy (Cont.)

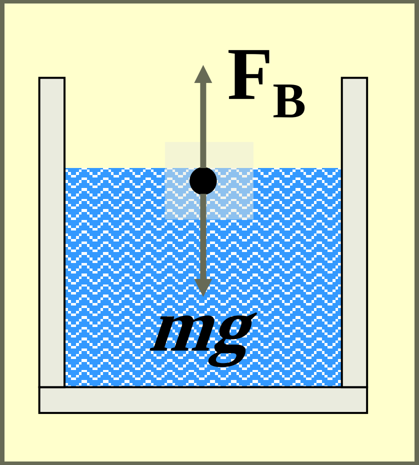
4. Archimedes' Principle: A submerged or floating object experiences an buoyant force equal to the weight of the displaced fluid:

$$F_B = m_f g = \rho_f g V_f$$

5. Remember: *m, r* and *V* refer to the *displaced fluid*. The buoyant force has nothing to do with the mass or density of the object in the fluid. (If the object is completely submerged, then its volume is equal to that of the fluid displaced.)

Problem Strategy (Cont.)

6. For a floating object, F_B is equal to the weight of that object; i.e., the weight of the object is equal to the weight of the displaced fluid:



$$m_x g = m_f g \quad \text{or} \quad \rho_x V_x = \rho_f V_f$$

Summary

$$Density = \frac{mass}{volume}; \quad \rho = \frac{m}{V}$$

$$\rho_r = \frac{\rho_x}{1000\ \mathrm{kg/m^3}}$$

$$\mathrm{Pressure} = \frac{Force}{Area}; \quad P = \frac{F}{A}$$

Fluid Pressure:

$$P = \rho g h$$

$$\text{Pascal:}\quad 1\ \mathrm{Pa} = 1\ \mathrm{N/m^2}$$

Summary (Cont.)

Pascal's Law:

$$\frac{F_{in}}{A_{in}} = \frac{F_{out}}{A_{out}}$$

Archimedes' Principle:

Buoyant Force:

$$F_B = \rho_f g V_f$$

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